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Analytical Support in Aircraft Certification

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1 Abstract

The high cost of designing a new airplane enforced engineers to look for new cheaper methods. One method for the cost reduction is wide use of computer simulations in designing and certification process. From many different methods of analysis, FEM appears to be the best, but in spite of all improvements, present level of fidelity is still too low to completely eliminate experiments in the designing process. This explains why Building Block Approach is still the main method for designing, but certification process, which is only verification one, is more suitable for use computer methods only. Results of static tests and FEM analysis for two airplanes designed in the Institute of Aviation will be shown in this presentation. To allow for comprehensive insight of the problem of fidelity of analysis, two different airplanes were selected. First one is the metal jet trainer I-22 Iryda designed according to the AP970 regulations and the second one - four places all-composite aircraft designed and certified according to the FAR.23 regulations.

2 Iryda I-22 and PZL I-23 Manager Aircraft

The I-22 and I-23 Manager aircraft are the newest products of the, operating for the last 70 years in Warsaw, Institute of Aviation (ILot). Founded in 1926, the Aviation Institute initially concentrated on testing and issuing certificate of airworthiness. After the WW2, it has broadened its scope of activity onto the design of flying apparatus of sorts. The successful designs of the first Polish, Gil (1946), and Zuk (1959) helicopters, were created here. A few training-fighter jets were designed as well, one of which, namely TS-11 Iskra won a set of world records to its name. A reconnaissance airship, and the line of rescue hovercraft vessel designs, were also successfully undertaken. The mentioned above training-fighter jets, were equipped with the series of the jet engines designed by the Institute, of which the most notable are the SO3 and K16.



Fig. 1 Last M96 version of training - fighter jet I-22 Iryda



Fig. 2 Personal & Business aircraft PZL I-23

Herein the latest version of the I-22 Iryda aircraft is presented. This is a highly maneuverable development version, where, in comparison to the previous one, the new wing with the Fowler flaps and LERX slots has been introduced, as well as the fin lengths increased, in order to provide additional stability at large angle of attack. The I-23 Manager is a single jet engine, low-wing monoplane provided with the classical tail units and tri retractable landing gear. The airframe structure is almost exclusively composites. Thanks to that and a thorough aerodynamics the 1200 km extreme range of the plane has been reached.

3 Design computations

The Institute of Aviation (ILot) customarily applies the three stage computational process, wherein increasing accuracy models are analyzed, for the designs of military and transport aircrafts.

First stage of analysis - choice of load cases for strength calculations.

The MEWA system worked out by the ILot is utilized at this stage. The idea of this being to use the superimposing of simple structural and aerodynamic models.

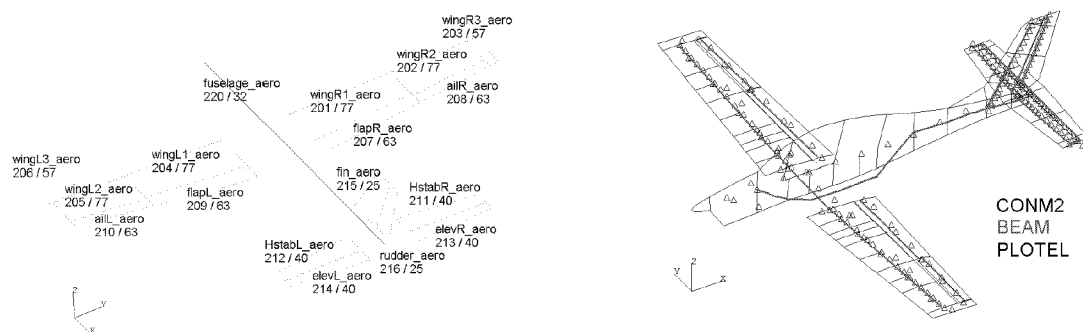


Fig. 3 PZL I-23 aerodynamic loads model

PZL I-23 structural loads model

The modified Multhopp's method is applied to determining aerodynamic loads. It yields very good results to the wings of moderate to high aspect ratio. The modification of the classical Multhopp's method entails complementing the Multhopp method by the calculations of the potential flow over once bent thin plate, so that the characteristics of the pitching moment, determined in aerodynamic tunnel, can be achieved.

The load, defined in such a manner, is later applied to the simplified by beams, model of the plane's structure. The resulting from the above distributions of moments and forces in the beams allows selecting critical load cases, dedicated for further analysis. Around a thousand different load cases are analyzed. For instance, for the PZL I-23 aircraft 14 mass variations were considered. This permitted to separate a certain group of load cases for further more detail strength calculations. In the concrete case of PZL I-23 aircraft 67 load cases were chosen for further computations.

Second stage computing model - general strength analysis

In this phase the Finite Element Method is usually used for analyzing of an aircraft as a whole or any of its main systems. To permit these models to be effectively utilized they have to be small. The upper limit of the FEM models built in the last decade of twentieth century, in ILot did not exceed 20 thousands elements. At present, thanks to the technical progress, the models can go up to 200 thousand elements. The twenty thousands number limit caused the global models to have low mesh density, roughly from 1 to 6 elements per one skin panel. The adopted accuracy, not permitting for in depth modeling of a plane detail, was not a problem, because adopted models served solely for determining the distribution of internal forces in members. It was so, because only in the third stage, the detail local analyzing of strength was performed.

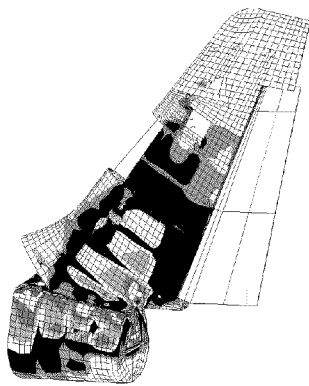


Fig. 4 Global FEM model of the I-22 aircraft vertical tail

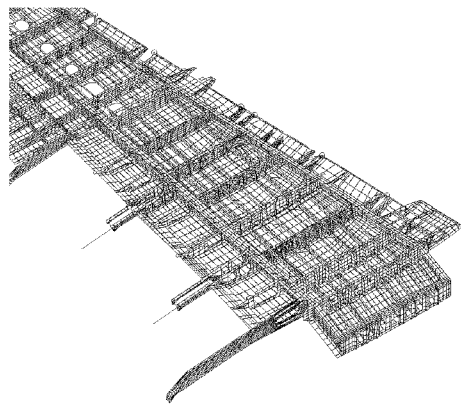
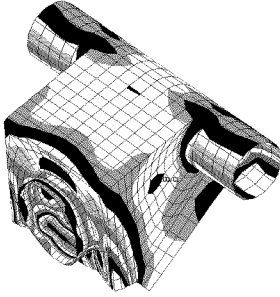
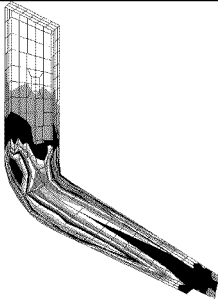
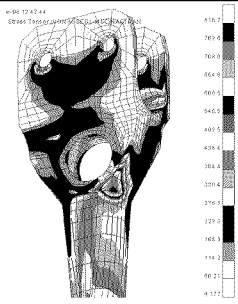


Fig. 5 Global FEM model of the wing, without the top skin, of the I-22 Iryda aircraft

Third stage computing model - local strength analysis

The internal loads determined in the previous stage serve now for the purpose of the strength analyzing of particular aircraft structural elements. Various calculating methods are applied at this stage - the mix of FEM and analytical methods, depending on the degree of complexity of the real object.

		
Fig. 6 PZL I-23 aircraft engine shock absorber seat.	PZL I-23 aircraft wing's flap fitting	I-22 aircraft flight controls component

Because the PZL I-23 has been classed as the tourist aircraft, in order to save costs of designing process, some simplifying approach was adopted in combining the two and three stages. In so doing a global computational model of increased accuracy was arrived at.



PZL I-23 Global FEM model

34.000 Elements
190.000 DOF

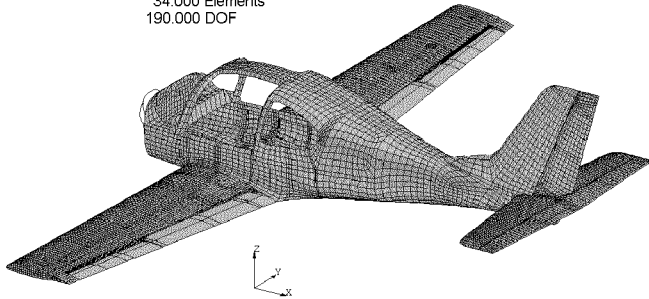


Fig. 7 PZL I-23 aircraft Global FEM model.

Size of the model rendered it impractical for calculations. It was therefore divided into separate models

- 1) Fuselage with engine frame
- 2) Wing
- 3) Horizontal Tail
- 4) Rudder
- 5) Flaps
- 6) Ailerons

A choice of models is presented below

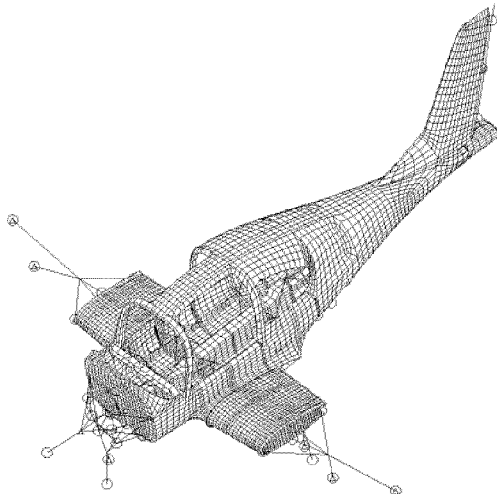
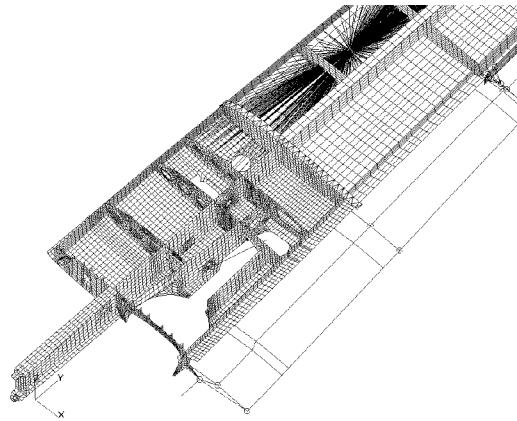


Fig. 8 Fuselage model of PZL I-23 aircraft



Wing model of PZL I-23 aircraft (view after top skin removal)

Strength calculations were performed using system MSC.Nastran in the case of PZL I-23 aircraft linear calculations were predominantly performed: linear static and linear buckling. In the case of metal made I-22 Iryda, non-linear calculations in full range of both geometry and material were performed.

The fact that the calculations for the PZL I-23 aircraft were limited to the linear bracket only, stems from the properties of composites are linear and for this type of structure one resigns off the structure work, once the stability has been lost.

The program RCS, devised by the ILOt, permits to analyze vast number of load cases thanks to "the automatic charging the model with load cases". For example, in the computations of the PZL I-23 aircraft, in total 67 cases of loading were taken into account. The fuselage was computed for 25 load cases, and the wing for 32 cases, engine frame for 13, horizontal tail for 6, rudder for 3, and the flaps for 2 loading cases.

In cases of laminated and composites structures to assess the strength the First Ply Failure hypothesis was applied. The strength of each ply was adjudicated by means of Tsai-Hill hypothesis. The allowable level of stress were determined as a result of material tests. On the PZL I-23 aircraft joints were predominantly glued and then screwed together to ensure the correct pressure in assembling. While assessing strength, the calculated intensities of the shear and normal forces in the joint were compared with the forces determined in the materials tests. A novelty being that in the calculations normal forces were allowed for, and not only shear forces.

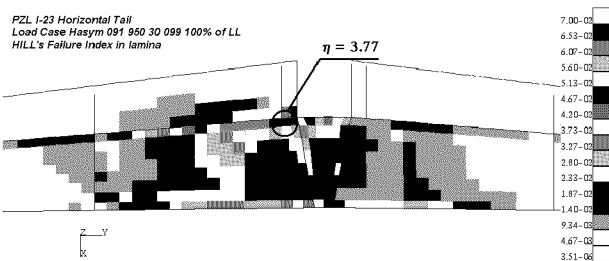
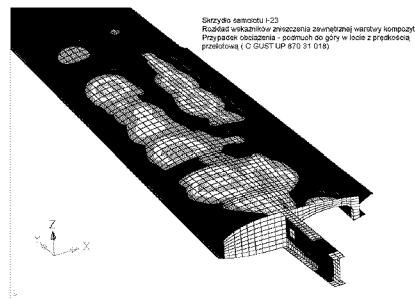


Fig. 9 Distribution of failure indexes in bottom skin of the horizontal tail of PZL I-23 aircraft



Distribution of failure indexes the wing skin of PZL I-23 aircraft

The metal structure strength was analyzed by checking the magnitude of von Mises stresses, found in the way of non-linear computations, with allowance for plasticity phenomenon.

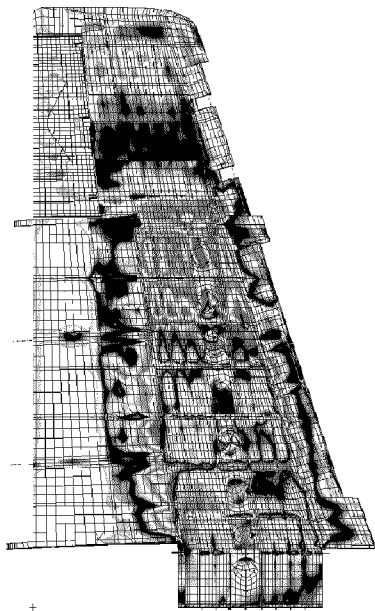
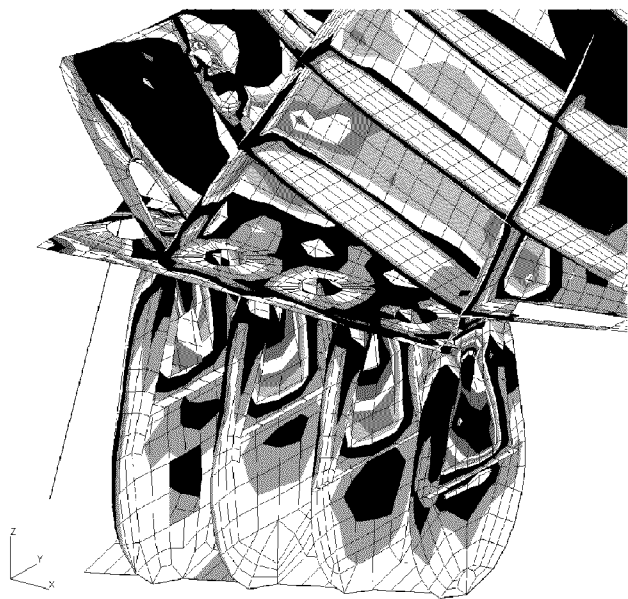


Fig. 10 Distribution of von Mises stress in wing of I-22 Iryda aircraft; load case – point D of the maneuvering envelope.



Distribution of von Mises stress in the junction of vertical tail with the bodywork of I-22 aircraft.

The performed computations not only allowed to design the structure, but to substantially decrease the number of load cases to conduct, during the static tests. Utilization of computer methods in aircraft design process, allows considering the influence of those cases on the design in question, which are not yet required by the regulations and standards in force. In the design of the structure of PZL I-23 aircraft, the results of the dynamic simulation of the whole vessel hitting the ground were taken into account, although the amendment 42 of FAR23 regulations, calls only for the dynamic check of the pilot - pilot's seat system.

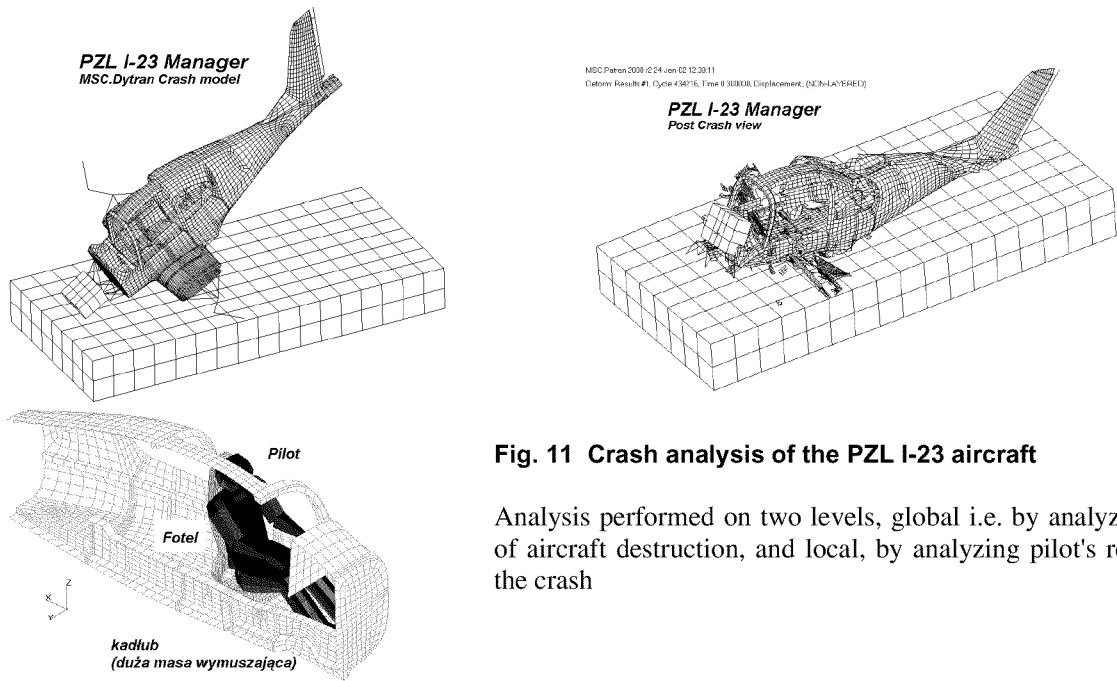


Fig. 11 Crash analysis of the PZL I-23 aircraft

Analysis performed on two levels, global i.e. by analyzing mode of aircraft destruction, and local, by analyzing pilot's reaction in the crash

4 Certification Process

For brevity sake, and also because the Iryda I-22 plane having been a military product, undergoes the different cycle of qualifying tests, we will here concentrate in some detail on the certification process of the composite aircraft PZL I-23 only. Because of the materials used in its construction, the PZL I-23 is not a typical aircraft, and for that reason the certification process must not completely resign from static tests. The FAR 23.307 regulation allows to apply - in the proving process of aircraft structures - analytical methods, provided that experience has already proved, these methods. In the case of PZL I-23 aircraft the computations performed allowed only to substantially reduce the number of load cases called for in the static trials.

Tab 1 Summary of strength tests of the PZL I-23 aircraft

No	Element investigated	Critical load case	Notes
1	Horizontal Tail	A Man Upd 950 30 091 Hasym091 950 30 099P	FAR 23.423(a), - A sudden deflection of the elevator controls
2	Pilot's seat	ELDC – 3 cases C GUST UP 630 15 018 Crash Test – 2 cases.	Emergency landing condition Positive Gust load FAR 23.333(c) Emergency landing dynamic condition – FAR 23.562 (b)
3	Aircraft controls	41 load cases	Lage number due to the lack of analysis
4	Wing flap	FL H GUST	A head-on Gust FAR 23.345 (c) (1)
5	Aileron	C AIL 950 30 052	Sudden aileron deflection - FAR 23.349 (b)(d)
6	Rudder	AV MAN 950 30 058 Mod	A Sudden rudder deflection FAR 23.441(a)(1)
7	Engine frame	9 load cases	
8	Fuselage	AV MAN 950 30 058 Mod A MAN UPd 950 30 091 Hasym009 825 21 078 L A 1150 Mod LL2P25 1117 28 103 ELC Complete turnover	Sudden rudder deflection. FAR 23.441(a)(1) Sudden elevator deflection FAR 23.423(a) Point A of the man. envelope. FAR23.333 (b) Level Landing - FAR 23. 479(a)(2)(ii) Complete turnover - FAR 23.561 (d) (2)
9	Wing	A 1150 Mod SL 950 30 109 LL2P25 1117 28 103	Point A of the man. envelope. FAR23.333 (b) Level Landing - FAR 23. 479(a)(2)(ii)
10	Landing gears	LL2P25 1117 28 103 SL 950 30 109 Dynamic testing	Level Landing - FAR 23. 479(a)(2)(ii)

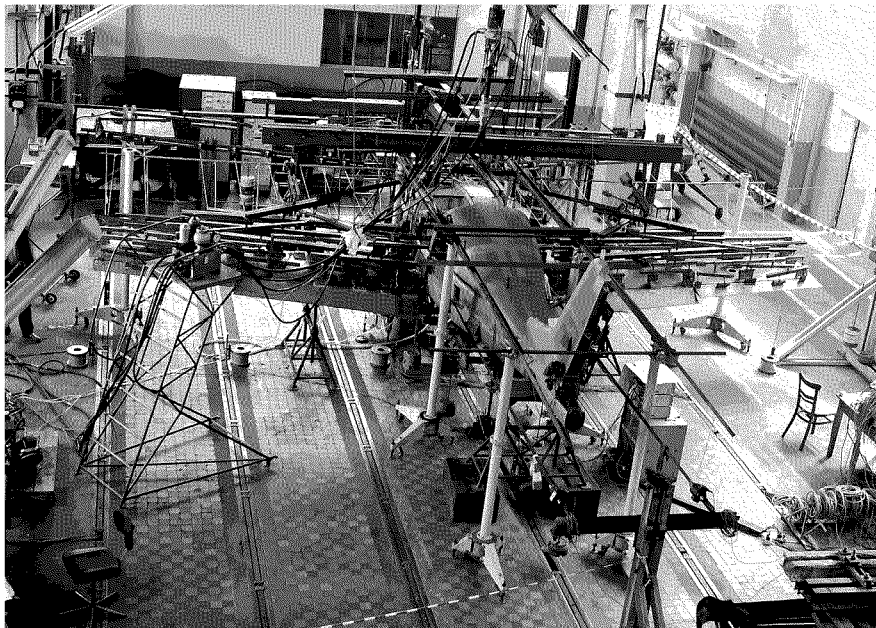


Fig. 12 PZL I-23 aircraft in the course of static tests – load case A 1150 Mod.

Depending on needs the testing were carried under two types of climatic conditions:

- room conditions (temp appr x 18 deg C, RH normal)
- hot conditions (temp appr x 55 deg C, RH elevated)

Due to the fact that PZL I-23 aircraft has been made of composites, two additional ultimate load factors were allowed.

ν_{dm} allowing for random distribution of material properties, and equal:

- ν_{dm} 1.19 For manually saturated elements. Determined on the ground of strength variability coefficient, in bending test of W-3 helicopter rotor blade coupons (WSK Swidnik)
- 1.10 For elements made by vacuum forming of prepregs in autoclave. Determined on the grounds of the manufacturer, CIBA, delivered data.

ν_{dk} - allowing for strength drop due to temperature and humidity

- $\nu_{dk} = 1.18$ For the whole structure, both for elements made of glass fabrics delivered by Interglass (fuselage) and for delivered by CIBA prepregs (wing). The coefficient value was determined no strength of the tests of material samples, conducted in ILot. The drop in value of dynamic shear modulus was taken as a criterion.

Furthermore the special coefficients given by FAR 23.619 and FAR 23.785 remain in force. Finally the following magnitudes for the ultimate load coefficient were taken:

Tab. 2 Coefficients of ultimate loads required

Element investigated	Test conditions	
	Room temperature	temp. 55deg C
Metal elements: engine frame, ribs, landing gears	1.5	1.5
Metallic seat fittings	2.0	2.0
Metal fittings (isolated tests)	1.725	1.725
Composite elements made by hand resin saturation: fuselage, empennage, seats	2.11 (1.5 * 1.19 * 1.18)	1.78 (1.5 * 1.19)
Composite elements made from prepregs in autoclave: wing, ailerons, flaps	1.95 (1.5 * 1.1 * 1.18)	1.65 (1.5 * 1.1)

As can be seen from the table, the two different values for ultimate load coefficients for the metal and composite components, render the static testing complicated. Subject to need this problem was handled in different manner:

- by using metal substitute elements in static testing conducted with the load exceeding 150% of limit load,
- over sizing fittings, so that they could take increased load.
- conducting static test up to the load level corresponding to the load capacity of metal component. The strength of a composite construction, for the missing load level was proven by calculations. The models take for such calculations were scaled from the results of static tests.

5 Verification of calculations

Majority of the static tests were simulated in calculations; in this way the information on the accuracy of calculations was gained. In course of the static tests the following were analyzed:

- strains in extreme layers of laminate and metal skin in the places where stresses concentration was expected
- inner forces in components eg: the engine frame rods, components of control system
- reaction forces in joining nodes, eg: wing-fuselage fitting
- structural displacements
- The beginning of instability were monitored

Due to space limitations only few chosen case with the closest to experimental results will be presented.

verification of strains in extreme layers of laminates

the measurements of the strains in the frame #1, performed during testing of the engine frame and the fuselage nose will serve as one verification example.

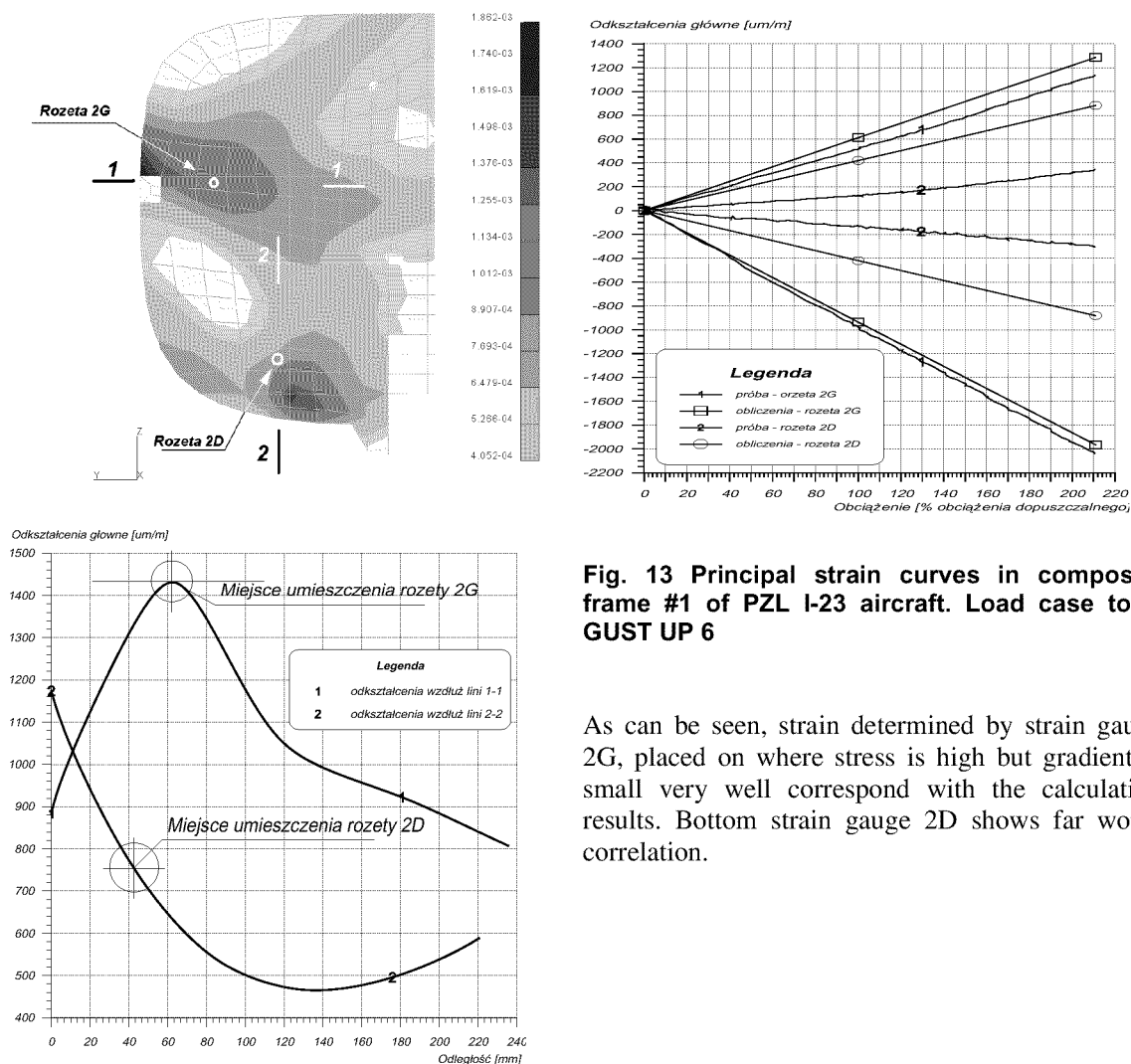


Fig. 13 Principal strain curves in composite frame #1 of PZL I-23 aircraft. Load case to C GUST UP 6

As can be seen, strain determined by strain gauge 2G, placed on where stress is high but gradient is small very well correspond with the calculation results. Bottom strain gauge 2D shows far worse correlation.

Verification of strains in metal skin

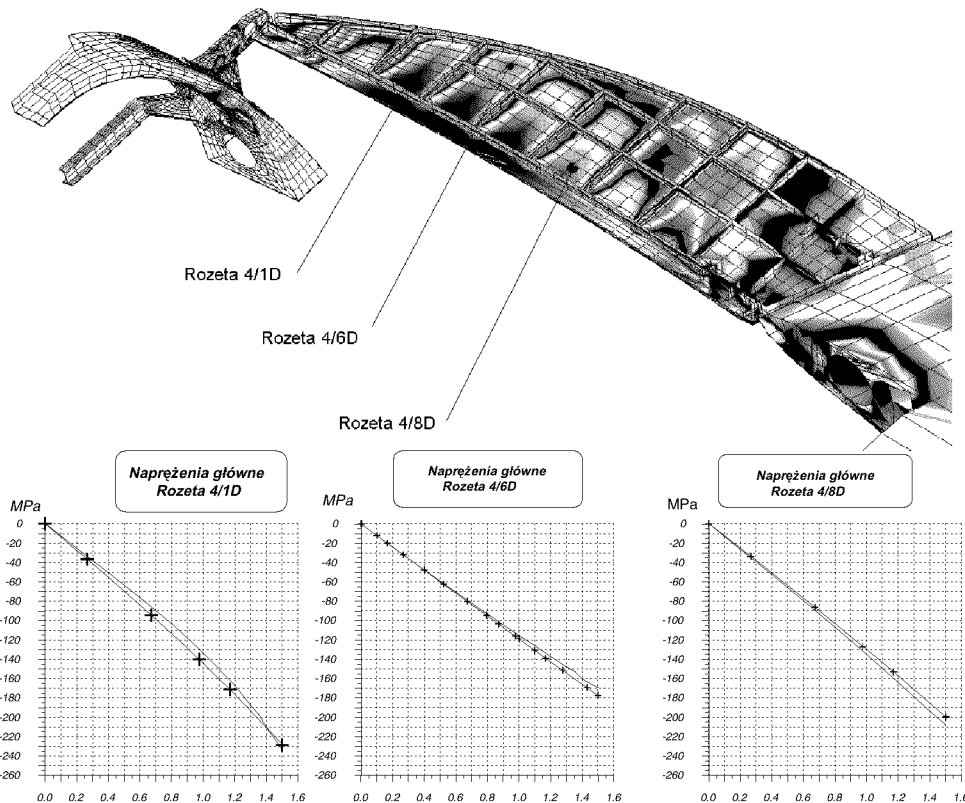


Fig. 14 Comparison of calculated results (+ denoted lines), with measured values during static testing, (smooth lines), in the wing strake (LERX slot) of the Iryda I-22 aircraft. The model for calculations was presented with the top skin "taken off", hence presenting the internal structure.

The comparison performed allowed to determine the calculation error, found from the formula:

$$\Delta = \frac{\text{test_results} - \text{calculated_results}}{\text{test_results}} \cdot 100\%$$

Tab 3. Verification of calculation summary

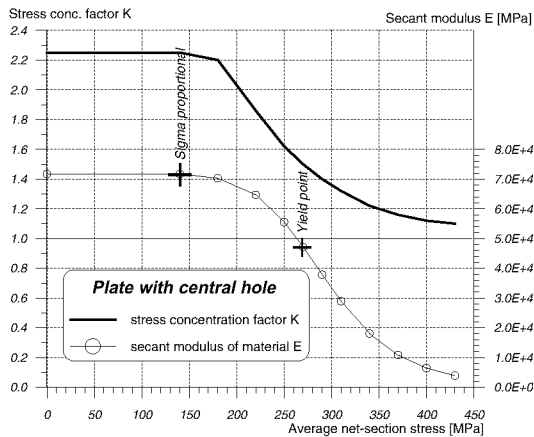
No	Criterion	Error
1	Strains in the laminate	62 %
2	Strains in the metal skin	56 %
3	Internal forces in components	24 %
4	Reaction forces in connections	15 %
5	Deformation	23 %

The tests conducted allow to draw following conclusions:

- 1) The presented global models of metal and composite aircrafts do not differ much in the quality of obtained results. The errors in determined internal force and deformation and stresses and strains are similar.
- 2) The origin of relatively large, 60% error is simple. In static tests one searches for places of highest stress, and to this purpose strain gauges are glued in places of parameters discontinuity or disproportion, like small holes, rigidity changes etc. the global models by their very nature do not allow for them, allowing

for presenting the overall work of structure. If gauges were glued in regular areas then the results would remind those for internal forces.

- 3) The plastic properties of metal structures, which composites lack, decide that the stress determination does not pose bigger problem in strength calculation of metal structures. The influence of plasticity is best shown while contemplating a simple tension of a notched plate. Otherwise regular stress distribution changes its character near the hole. In some areas the stresses increase and in other decrease. The ratio of the maxim undisturbed stress to disturbed is called stress concentration factor. Its value depends not only on the sample's geometry but also from the stress (strain) magnitude.



The graph presents that stress concentration factor decreases as yield stresses increases. On reaching ultimate tensile stress level the notch influence is negligible - the factor is close to 1.0

The presence of this phenomenon compensates inaccuracies of models used to assess the strength of metallic constructions. In case of composites their characteristics is linear. Stress concentration near notch exists in the whole regime of structure working, demanding detail, local models, similar to those used in fatigue calculations. Optionally, additional safety factors should be used in calculations.

Fig. 15 Stress concentration factor

6 Conclusions

The works conducted in ILOt allow for following conclusions:

- 1) The state-of-the-art computational techniques do not yield the sufficient accuracy of results, so that the static tests could be abandoned.
- 2) In spite of relatively large stress determining errors static tests of metal structures generally run without major surprises, contrary to composite structures. The forgiving lack of failure in metal structures, in spite of not accounting for most of stress concentrations, is largely due to the plasticity phenomenon, absent in composites.
- 3) The application of additional safety coefficients for composite structures renders static testing complicated and more expensive. To avoid over sizing of metal components, computational proving of their strength sufficiency is necessary.
- 4) Necessity to use very particular computational models for composite structures, requires creating additional management systems for local models, so that very complex strength calculations might be more effective
- 5) Because still insufficiently developed theory of laminated materials, it seems mandatory to apply for the calculations additional safety factors, thus wasting possible mass benefits.